Wave Propagation in Granular Media Including Marine Sediments

M. J. Buckingham (SSN 033-66-6166)
Marine Physical Laboratory
Scripps Institution of Oceanography
University of California, San Diego
8820 Shellback Way
La Jolla, California 92093-0238
tel: (858) 534-7977; fax: (858) 534-7461; email: mjb@mpl.ucsd.edu

Grant number: N00014-93-1-0054
http://extreme.ucsd.edu/ADONIS.html

LONG-TERM GOALS

The long term objective is to characterize the wave properties of marine sediments in the frequency band between 100 Hz and 100 kHz.

SCIENTIFIC OBJECTIVES

Our sediment research includes three main thrusts: (1) development and refinement of a theoretical model of wave propagation in saturated granular media; (2) at-sea experiments to determine sediment properties, including *in situ* measurements of wave propagation in the atmosphere, the water column and the sediment, to provide experimental data for validation of the theoretical model; and (3) controlled experiments in an "ideal" sediment consisting of spherical, uniform-size glass beads in a laboratory tank.

APPROACH

Part 1. Theory

A theoretical model of wave propagation in saturated, unconsolidated porous media such as a marine sediment has been developed, based on the micro-physics of sliding at grain-to-grain contacts. The argument involves the non-linear properties of the thin film of fluid separating adjacent grains. Intergranular interactions give rise to dissipation and dispersion, and these effects are accommodated by a new stress tensor in the Navier-Stokes equation, which, in the usual way, separates into two wave equations, one for compressional waves and the other for shear waves. The theory itself is analytical, yielding simple algebraic expressions for the wave speeds and attenuations. These dispersion relations involve just three independent parameters.

Part 2. At-sea measurements

a) Airborne-source experiments
A light aircraft (Socata Tobago TB10), flying at low altitude (33 to 330 m), is used as a source of sound for making low-frequency (100 Hz to 1 kHz) measurements of sound speed and attenuation in the sediment. Receivers are in the atmosphere about 1 m above the sea surface (a microphone), in the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Wave Propagation in Granular Media Including Marine Sediments**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Marine Physical Laboratory,Scripps Institution of Oceanography,,University of California, San Diego,8820 Shellback Way,,La Jolla,,CA, 92093**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long term objective is to characterize the wave properties of marine sediments in the frequency band between 100 Hz and 100 kHz

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

water column (a vertical array of hydrophones), and buried about 75 cm deep in the sediment (a hydrophone and a bender for detection of shear waves). A Sea Bird temperature profiler is deployed to obtain the sound speed profile in the water column, and all navigation (aircraft and surface vessel) is performed with hand-held GPS units. Sound speed in the sediment is obtained directly from the difference between the Doppler shifted frequencies on approach and departure of the aircraft. Sediment attenuation is returned from the increasing amplitude of the sediment arrival as the aircraft closes on the sensor station. Active contributors to these on-going experiments are: Eric Giddens (SIO graduate student); Thomas Hahn (SIO post-doctoral fellow); Jonathan Pompa (SIO graduate student); Fernando Simonet (SIO engineer and diver); Matthew Alkire (undergraduate, SIO summer intern).

b) Bottom reflection-coefficient measurements
In-situ measurements of the normal-incidence bottom reflection coefficient are being made at the SAX99 site in shallow water in the Gulf of Mexico. The experimental procedure is based on a pyramid-type structure formed by thin, nylon fishing line. The lower corners of the pyramid are attached to screw anchors in the sediment, and a vertically aligned source and receiver are suspended from the apex, which is a couple of meters above the bottom. This arrangement minimizes interference from spurious reflections from the supporting structure. Divers install the system at each deployment, taking about 20 minutes to insert the screw anchors, arrange the pyramid, and attach the source and receiver. The technique is simple and successful, yielding large data sets quickly and economically. Participants in these experiments were: Eric Giddens (SIO graduate student); Thomas Berger (SIO post-doctoral fellow and ONR Young Investigator); Fernando Simonet (SIO engineer and diver).

Part 3. Tank experiments

Our laboratory tank is 2 x 3 m in area and 1.6 m deep. It has been half filled with six tonnes of uniform, spherical, 0.3 mm diameter glass beads, whose mechanical properties are known. Freshwater is used in the tank, continually circulating under UV light to eliminate contamination by microbial organisms. Small quantities of chlorine help maintain the cleanliness of the water and sediment. This system has been operating for well over a year, with no sign of biological contamination. Air was removed from the glass-bead sediment by vacuum pumping before installation in the tank. *In-situ* probes (sources and receivers) in a four element configuration are being used for measuring compressional and shear wave properties over as many decades of frequency as possible. Reflection-coefficient measurements of the sediment surface will also be made. Participants in these experiments are or were: Eric Giddens (SIO graduate student); Thomas Berger (SIO post-doctoral fellow and ONR Young Investigator); Fernando Simonet (SIO engineer).

WORK COMPLETED

The unified theory of wave propagation in saturated granular materials has been developed and published in a series of five papers in the Journal of the Acoustical Society of America. A discussion of the high-precision correlations emerging from the theory has been published in the Journal of Computational Acoustics.

Between March and July 2002, five flying experiments were performed over a sensor station located about 1.5 km north of Scripps pier and 1 km west of the coast near La Jolla, southern California (32˚ 53.889’ N, 117˚ 15.718’ W). The flying time for each experiment was approximately 1.5 hours. Extensive data sets have been collected from all sensors, in the atmosphere, the water column and buried in the sediment, which consists of a very fine sand, essentially free of inclusions such as shell fragments. (The signal on the shear sensor in the sediment was predominantly due to the p-wave, which entirely masked the s-wave, if the latter were present at all). Our preliminary findings have been reported in papers published in Acta Acustica, the Journal of Computational Acoustics and the Proceedings of the European Conference on Underwater Acoustics.

Two at-sea experiments in the Gulf of Mexico, one off Panama City and the other off Fort Walton Beach at the SAX'99 site, have been performed in which the normal-incidence reflection coefficient of the seabed was measured over a range of frequencies between 5 and 40 kHz.

RESULTS

1) The new theory of wave propagation in marine sediments accurately represents the speed and attenuation data for compressional waves above about 2 kHz. It also matches the few shear wave data that are available. The theory is internally consistent and yields many of the sediment properties once the compressional speed has been specified. Nevertheless, there is a pressing need for more data, particularly at low frequencies, below 2 kHz, for the compressional wave and at all frequencies for shear. Shear attenuation data are important for testing the theory but are largely unavailable at present.

2) Our flying experiments have yielded the following observations, which we believe have never been made before.

a) Simultaneous recordings of the airborne and water-borne acoustic signature of an over-flying light aircraft.

b) Detection of the acoustic signature of a light aircraft by a sensor buried in the sediment.

c) Simultaneous recordings of the airborne, water-borne and sediment-borne acoustic signature of an over-flying light aircraft.

A new technique, based on the difference between Doppler-shifted frequencies on aircraft approach and departure, has been developed, which yields the local sound speed in the medium where the sensor is located. Using this technique on a data set acquired during one of the overflights of 2 July 2002, preliminary estimates for the sound speed in the atmosphere, the water column and the sediment at a nominal frequency of 700 Hz are: 334 m/s (340 m/s) for air; 1527 m/s (1517 m/s) for sea water; and 1617 m/s for very fine sand sediment. The numbers in brackets are known values from direct measurements, and give some sense of the accuracy of the Doppler technique. We expect to improve the precision of the estimates by reducing the frequency cell width in the Fourier analysis of the Doppler data, and by averaging over as many as 20 overflights.

3) The reflection coefficient experiments show that the ripple field of a natural, sandy seabed causes significant variations in the reflection coefficient, anywhere between -6 and -15 dB. The variability is interpreted as being due to the focusing and defocusing by the troughs and peaks, respectively. After divers smoothed the seabed, the reflection coefficient was found to be much more stable at approximately -8 dB, which agrees with Rayleigh's expression for the reflection coefficient.

4) Research on the acoustic radiation from the bubble plume formed by a plunging water jet, which we conducted in the same laboratory tank containing the glass-bead sediment, has been completed. A paper describing our results and including a theory of the natural resonances of the bubble plume has been accepted for publication in the Proceedings of the Royal Society, London, Series A.

IMPACT/APPLICATIONS

The development of the new theory on wave propagation in saturated porous media is important for understanding and interpreting the physics of waves in marine sediments. This is relevant to acoustic propagation modeling in shallow water, where bottom interactions are significant, and to the development of inversion techniques for determining ocean-sediment environmental properties.

Our experiments with a light aircraft as a sound source for underwater acoustics applications have been more successful than we ever imagined and have opened up new ways of acquiring information about ocean processes. In particular, the Doppler technique for returning the low-frequency sound speed in the sediment from a single buried sensor has returned unique information with precision far superior to that available from previous methods. Our results to date really only scratch the surface but suggest that aircraft sound sources have potential for many underwater acoustics measurements, most of which have still to be explored.

TRANSITIONS

Since the work on sediments is still under way, it is too early to consider transitioning. However, one group, headed by Dr. K. A. Naugolnykh, CIRES, University of Colorado/NOAA, Environmental Technology Laboratory, Boulder, Colorado, has applied the theoretical ideas to the case of non-linear, laser-generated sound pulses in a granular medium. They found that the new theory agreed very satisfactorily with their results.

RELATED PROJECTS

U.S.A.

1. Dr. Michael Richardson, N.R.L., Stennis, and I are collaborating on the interpretation of sediment wave property data obtained using his ISSAMS frame. This includes the re-assessment of travel-time measurements and the development of techniques for making high-accuracy sound speed and attenuation measurements in sediments. (Paper to appear in the IEEE J. Ocean. Eng. Special Issue on SAX99).

2. I was an active participant in the ONR supported SAX99 experiment conducted in the Gulf of Mexico and expect to be involved in the follow-up experiment, SAX04, planned for 2004. Chief Scientist in both experiments is Dr. Eric Thorsos, APL, University of Washington.

3. Dr. Alex Tolstoy and I are collaborating on the application of Matched Field Processing to hydrophone data generated by a fast-moving airborne source (*i.e.,* an aircraft). We hope to apply MFP to the data we have already collected at SIO to obtain a quantitative description of the ocean-sediment environment in the vicinity of the receivers.

4. Prof. Giorgio Gratta, Stanford, and I are working on the underwater acoustic detection of extremely high energy neutrinos. Data for this project are being obtained from the U.S. Navy's AUTEC range off Andros Island, Bahamas. (Paper published in J. Astroparticle Phys.)

Canada

1. Prof. Ross Chapman, University of Victoria, B.C., and I are collaborating on measuring the interface-wave properties of the bottom using a “hush gun”, a type of quiet air gun. In particular, we plan to determine the low-frequency (100 Hz to 1 kHz) sound speed in the sediment from the head wave, probably at a site just north of Scripps pier, off La Jolla, California.

United Kingdom

1. Dr. Sam Marks, Defence Evaluation and Research Agency (DERA), Winfrith, holds an extensive data set of sediment properties from world-wide locations. We are currently exploring ways of using these data to help in the theoretical development.

2. Dr. Gary Heald, DERA, Winfrith and Dr. Nicholas Pace, University of Bath (currently at SACLANTCEN, La Spezia, Italy) are collaborating with me in developing laboratory and in situ experiments aimed at determining sediment wave properties, particularly P-wave dispersion, from measurements of the reflection coefficient of the seafloor.

3. Dr Alastair Cowley, DERA, Winfrith is collaborating with me on phased array techniques applied to acoustic daylight imaging. He and his team of engineers recently conducted tests in San Diego Bay using our ADONIS array head of 128 hydrophones with their high-speed beamformer. This phased array system, without the spherical reflector that was used in our original acoustic daylight experiments, yielded recognizable images of targets at ranges of approximately 10 m solely from the acoustic illumination provided by the ambient noise in the ocean.

France

1. Dr. Jean-Pierre Sessarego, Laboratoire de Mecanique et d’Acoustique, C.N.R.S., Marseille, has a laboratory-based experimental program on acoustic waves in sediments. We are currently planning a cooperative effort with this laboratory aimed at testing, under controlled conditions, some of the predictions of my new theory.

PUBLICATIONS

1. M.J. Buckingham, “On the phase speed and attenuation of an interface wave in an unconsolidated marine sediment,” *J. Acoust. Soc. Am.*, **106**, 1694-1703 (1999).

2. M.J. Buckingham, “Theory of compressional and transverse wave propagation in consolidated porous media,” *J. Acoust. Soc. Am.*, **106**, 575-581 (1999).

3. M.J. Buckingham, “Acoustic daylight imaging in the ocean,” in *Handbook on Computer Vision and Applications*, vol. 1, Sensors and Imaging, B. Jähne, H. Haubecker, and P. Geibler, Eds. San Diego: Academic Press, 1999, pp. 415-424.

4. C. L. Epifanio, J. R. Potter, G. B. Deane, M. L. Readhead, and M. J. Buckingham, "Imaging in the ocean with ambient noise: the ORB experiments", *J. Acoust. Soc. Am.*, **106**, (6), 3211-3225 (1999)

5. M.J. Buckingham, “New theoretical basis for determining the geoacoustic parameters of the seabed,” in *Experimental Acoustic Inversion Methods for exploration of the shallow water environment*, A. Caiti, J.-P. Hermand, S.M. Jesus, and M.B. Porter, Eds. Dordrecht: Kluwer, 2000, pp. 195-209. [INVITED].

6. M.J. Buckingham, “Wave propagation, stress relaxation, and grain-to-grain shearing in saturated, unconsolidated marine sediments,” *J. Acoust. Soc. Am.*, **108**, (6), 2796-2815 (2000).

7. M.J. Buckingham, “Wave propagation in saturated porous media,” in *Proceedings of the First International Conference on Acoustics, Noise and Vibration*, vol. **in press**, A. Guran, Ed. Montreal, (2000). [KEYNOTE ADDRESS].

8. M.J. Buckingham and M.S. Garcés, “Airborne acoustics of explosive volcanic eruptions,” *J. Comp. Acoust.*, **in press** (2000). [KEYNOTE ADDRESS].

9. M.J. Buckingham, “Precision correlations between the geoacoustic parameters of an unconsolidated, sandy marine sediment,” *J. Comp. Acoust.*, **9**, (1), 101-123 (2001). [INVITED].

10. A. Cowley, R.A. O'Leary, F. Simonet, T.K. Berger, and M.J. Buckingham, “Acoustic Daylight imaging in underwater environments,” Proc. Fifth European Conference on Underwater Acoustics, Lyons, **1**, 375-380 (2000).

11. M.D. Richardson, K.B. Briggs, D.L. Bibee, P.A. Jumars, W.B. Sawyer, D.B. Albert, T.B. Berger, M.J. Buckingham, N.P. Chotiros, P.H. Dahl*, et al.*, “Overview of SAX99: environmental considerations,” *IEEE J. Ocean. Eng.*, **26**, (1), 26-53 (2001).

12. M. J. Buckingham, "Acoustical oceanography in perspective", Proc. Inst. Acoust. Conf. on Acoustical Oceanography, T. G. Leighton, G. J. Heald, H. D. Griffiths, and G. Griffiths (eds), Bath Univ. Press, **23**, 2, 1-10, (2001) [KEYNOTE ADDRESS].

13. M. J. Buckingham, "Wave propagation in dispersive marine sediments: a memorial to David G. Crighton", Proc. Fifth Int. Conf. Theoretical & Computational Acoustics, Beijing, May 21-25, E. C. Shang (ed.), 32-33 (2001) [KEYNOTE ADDRESS].

14. M. J. Buckingham, "Wave propagation in dispersive marine sediments: a memorial to David G. Crighton", *J. Comp. Acoust.*, **in press**.

15. N. G. Lehtinen, A. Shaffique, G. Gratta, T. K. Berger, M. J. Buckingham, "Sensitivity of an underwater acoustics array to ultra-high energy neutrinos", *J. Astroparticle Physics*, **in press** (2001).

16. M. J. Buckingham and T. K. Berger, "Low frequency sound from a bubble plume", Proc. 17th Int. Conf. on Acoustics, Rome, Italy, 2-7 September 2001, A. Alippi (ed.), [KEYNOTE ADDRESS].

17. T. R. Hahn, T. K. Berger and M. J. Buckingham, “Acoustic resonances in the bubble plume formed by a plunging water jet”, *Proc. Roy. Soc.*, **in press**.

18. M. J. Buckingham, E. M. Giddens, J. B. Pompa, F. Simonet and T. R. Hahn, “Sound from a light aircraft for underwater acoustics experiments”, *Acta Acustica*, **in press**.

19. M. J. Buckingham, E. M. Giddens, J. B. Pompa, F. Simonet and T. R. Hahn, “A light aircraft as a source of sound for performing geo-acoustic inversions of the sea bed”, Proc. 6th European

Conference on Underwater Acoustics, Gdansk, Poland, 24-27 June 2002, A. Stepnowski (ed.), pp. 465-470. [INVITED].

20. M. J. Buckingham and M. D. Richardson, "On tone burst measurements of sound speed and attenuation in sandy marine sediments", *IEEE J. Ocean. Eng., Special Issue on SAX99*, **in press**.

21. M. J. Buckingham, E. M. Giddens, J. B. Pompa, F. Simonet and T. R. Hahn, "An airborne sound source and an ocean receiver for remote sensing of the sea bed", Proc. 6th Pan Ocean Remote Sensing Conference (PORSEC), Bali, Indonesia, 3-6 September 2002, B. P. Pasaribu, R. Kaswadji, I. W. Nurjaya and J. L. Gaol (eds.), pp. 203-207.

22. M. J. Buckingham, E. M. Giddens, J. B. Pompa and F. Simonet, "Preliminary experiments on light-aircraft noise as the source of sound in ocean-acoustic inversion applications", Proc. First International Conference on Inverse Problems: Modelling and Simulation", Fethiye, Turkey, 14-21 July 2002, A. Hasanov (ed.). [INVITED].

23. M. J. Buckingham, E. M. Giddens, F. Simonet and T. R. Hahn, "Propeller noise from a light aircraft for low-frequency measurements of the speed of sound in a marine sediment", *J. Comp. Acoust.*, **in press**.

24. M. J. Buckingham, E. M. Giddens, F. Simonet and T. R. Hahn, "Wave properties of sediments determined using the sound of a light aircraft", Proc. International Conference on Sonar-Sensors and Systems (ICONS-2002), 11-13 December 2002, Cochin, India, H. R. S. Sastry (ed.), **in press**. [KEYNOTE ADDRESS].